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Reciprocal frames: an ancestral structural principle to use native wood species in Chile

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ABSTRACT: Using native wood species instead of introduced wood ones, like Radiata Pine (*Pinus radiata*), has lots of positive consequences from an environmental approach: 1) does not acidifies the soil, 2) makes possible to preserve native flora and fauna. Also, Roble (*Nothofagus obliqua*), Rauli (*Nothofagus alpine*) and Coïgue (*Nothofagus dombeyi*) are the most common native species and have very good structural properties compared to introduced ones. In Chile, regarding primary economic activities, forestry represents 19%. A percentage similar to the contribution to GDP of the agricultural market. However, even if today native species of wood represents 80% of surfaces of forest in the country, the exportation of native wood species represents only 2% of the total wood exportation. Also, in the local market nowadays, native species are used mainly as firewood. Could it be possible, thanks to the study of geometry, specifically an ancestral structural principle called reciprocal frames, to build big spans using only small battens? Is it possible to build structural components avoiding the use of glue or any other chemical products that have negative consequences on the environment? Platform-frame systems in Radiata Pine used for walls or for slabs could be replaced for this type of structural components?

KEYWORDS: nexorade, structural simulations, geometrical studies, revival of ancestral materials

1. INTRODUCTION

We chose wood as the primary material because of its environmental benefits. Wood is: 1) a material that is both renewable and recyclable, 2) one cubic metre of wood stores about one ton of CO_2, as in [1], 3) it has been demonstrated that increasing the use of wood in construction by 17% reduces carbon emissions to the atmosphere by 20%, as in [2], 4) the grey energy required for the transformation of one metre of wood corresponds to 80% of the consumption for concrete transformation and 2% of the consumption for steel transformation, as in [3].

We chose untreated wood, free of glue and free of any other chemical products. We excluded glue because most glues emit formaldehyde, a toxic component that has recently been shown to be carcinogenic, as in [4]. Even though using chemicals products may improve the characteristics of wood, they are also excluded from this research because they are inconsistent with their environmental goals.

We prefer native species of wood because of their natural durability. In other words, they are more resistant to biohazards (termites, bacteria, or fungi) or can withstand them equally to introduced species that have been impregnated. Nonetheless, the most part of impregnation treatments in Chile are with chemical products such as CCA (Chrome, Copper, and Arsenic), which is prohibited in countries such as France due to its toxicity, as in [5]. Some introduced species, such as the Radiata pine (Pinus radiata), present significant biological pollution risks, as in [6].

On top of this, the national native sawn wood production it's been progressively decreasing, preferring Pino Radiata (*Pinus radiata*) and other species. The 2020 formal production of native sawn wood were of 75.714 m3, 34,8% (26,363 m3) Lenga (*Nothofagus pumilio*), 22.6% (17.092 m3) Roble (*Nothofagus obliqua*), and 14.9% (11.282 m3) Coïgue (*Nothofagus dombeyi*), as in [7]. Approximately, 9 million cubic metres of firewood are used per year, as in [9], where 85,9% are native species, as in [8]. On top of this, firewood exploitation is done in an informal way, as in [9], without environmental management, and being the first cause of degradation of the native forest in Chile.

We select a reciprocal frame that is a structural principle made of battens that are supported one after the other. The point where battens meet is called a "nexor". We divide this structural principle into two categories: one where elements of the structure have a different role, and the other where all elements have the same one, as shown in

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Figure 1, Figure 2, and Figure 3. We choose this principle instead of another one because it allows us to construct big spans only using short battens. Other structural principles with the same characteristics are tensegrity and interlaced carpentry. The first one is based on a system of isolated components under compression inside a network of continuous tension and arranged in such a way that the compressed members do not touch each other while the prestressed tensioned members delineate the system spatially, as in [10]. The second one is also called interlaced carpentry, in Spanish "*carpintería de lazo*" that means a carpentry made of bows, as in [11]. It is defined also as a combination of "wheels", in Spanish "*ruedas*", as an analogy between the wheel used in mechanics and the wheel drawing method based on the rotation of lines having a point as the centre. Nevertheless, the first one is a system with different materials and different thicknesses and in consequence it has a more complex constructive process. The second one, even choosing the simplest "*rueda*" requires cutting wood on many different angles. In consequence, both constructive systems require more time and are more expensive than the reciprocal frame one.

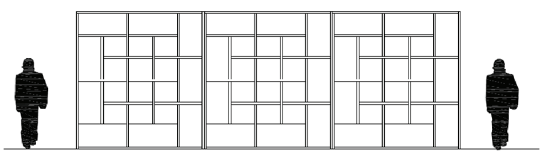

Figure 1. Type A: Reciprocal frame wall, with four jigs

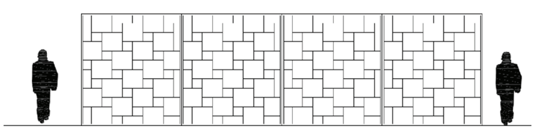

Figure 2. Type B: Reciprocal frame wall, with two jigs

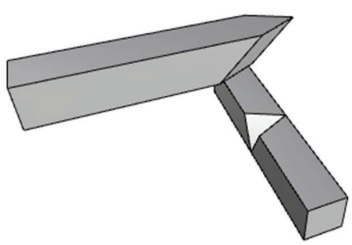

Figure 3. Construction detail of type B jigs

2. METHODOLOGY

We present the criteria considered for the purpose of this paper: a species selection, followed by a geometry selection and at the end a structural selection.

2.1 SPECIES SELECTION CRITERION

To select wood to be used, seven criteria were considered, using the database previously created (Caicedo y Segeur, 2021).

The following criteria, were selected:

C1 Origin of the wood, selecting native wood and excluding introduced species.

C2 Species conservation, excluding species at risk (NT), endangered (EN), or vulnerable (VU).

C3 Mechanical characteristics. The selection was done by their largest compressive parallel to grain stress.

C4 Mechanical characteristics. The selection was done by their largest compressive perpendicular to grain stress.

C5 Natural durability to bio- hazard, avoids the use of chemicals and others to protect the wood from the environmental conditions of the site.

C6 Capacity to dry naturally.

C7 Availability on the market.

Criteria C3, C4, C5, C6, is a numerical ordering value. Criterion C1, C2, C7 is an exclusion selection.

2.2 GEOMETRY SELECTION CRITERION

Several patterns of reciprocal structures were explored, using the geometry of the square as a basis, evaluating the ease of fabrication, assembly, and transport of each one of them. In figure 4 is shown reciprocal frame wall with four jigs. In the circles red and purple are shown the different types of joints. In yellow, pink, blue and green are shown the jigs. In figure 5 is shown a reciprocal frame wall with two jigs. On both examples the joint type is the one that determine the number of jigs. We exclude a different type of jig when the batten only needs to be cut when it is located on the periphery of the panel.

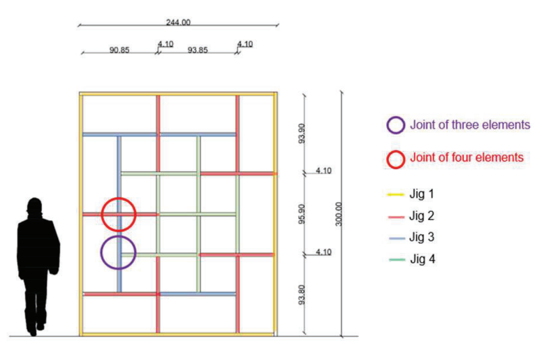

Figure 4. Reciprocal frame wall with four jigs.

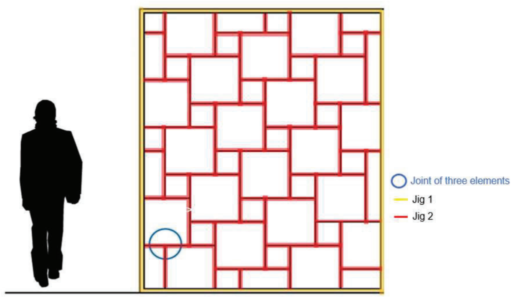

Figure 5. Reciprocal frame wall with two jigs.

To create models with different geometries we parameterized prototypes allowing us to make modifications with relative ease, developing adjustments to improve the performance of the whole system. We used the software Rhinoceros, more specifically a plug-in called Grasshopper as in Figure 6.

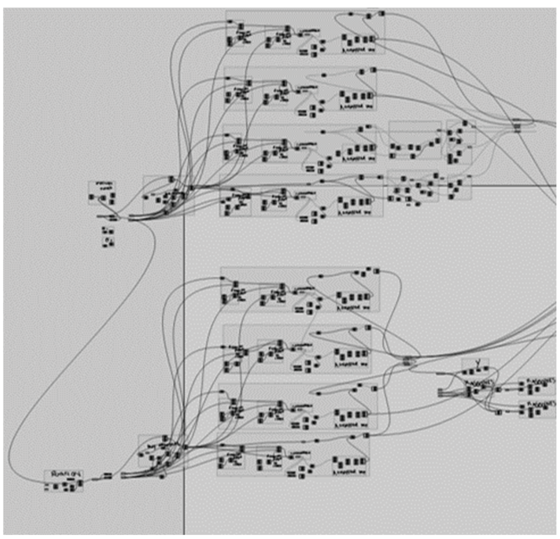

Figure 6. Algorithm wrote in Grasshopper to create different geometries.

Among the parameters used, the following two aspects were considered: batten morphology, and batten geometry. More specifically, the location of joints and the shim between them. In figure 7 is shown a jig modelled in Rhinoceros.

One of the aspects to consider is the size of joints. There is a 0,33 mm gap between the batten and the void where the batten will be placed in the 3D printing prototypes. This gap will have to be adjusted again when changing scale and materiality between models. Reaching a more accurate solution when working with native wood species.

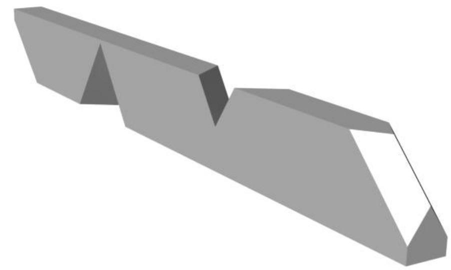

Figure 7. Jig modelled in Rhinoceros

2.3 STRUCTURAL SELECTION CRITERION

The third step was to compare structural simulations and budgets of a typical Radiata Pine (*Pinus radiata*) platform-frame module with a native wood species one based on a reciprocal frame. Because the mechanical properties of native species are better than the Radiata Pine (*Pinus radiata*) ones, the section of the first one is smaller.

For this purpose, preliminary evaluations of the prototype structure were carried out considering a 1.2 * 2.4 metres frame, since this module corresponds to the standardised wood measurements sold in Chile.

3. RESULTS

3.1 SPECIE SELECTION RESULTS

We gathered information from thirty-four wood species. From them, only thirteen can be considered because they fulfil criteria C1 and C2, origin and conservation respectively.

In figure 8 is shown a ranking of compressive parallel to grain stress of Chilean native wood species according to criteria C3.

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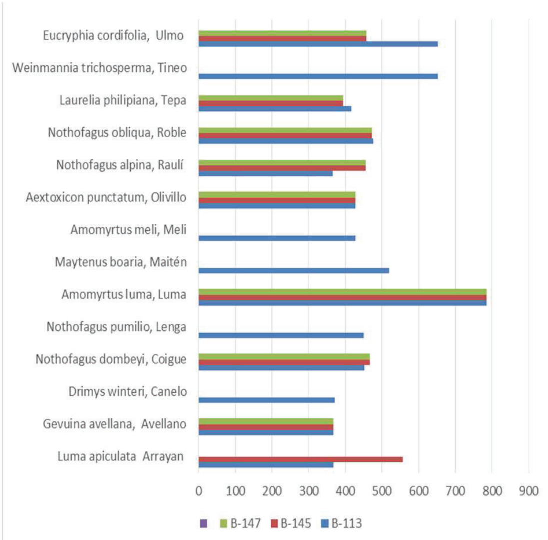

Figure 8 Ranking of compressive parallel to grain stress of Chilean native wood species

In figure 9 is shown a ranking of compressive perpendicular to grain stress of Chilean native wood species, according to criteria C4.

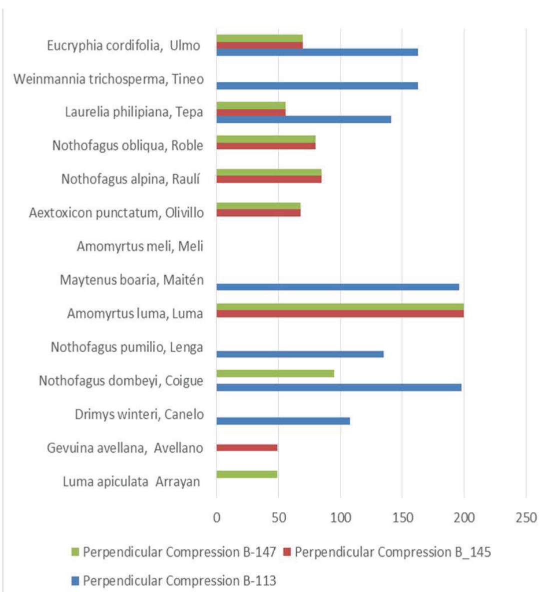

Figure 9 Ranking of compressive perpendicular to grain stress of Chilean native wood species

In figure 10 we present a ranking of natural durability to biohazards of Chilean native wood species

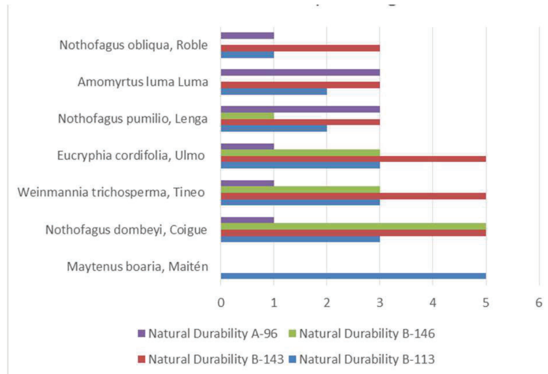

Figure 10 Ranking of natural durability to biohazards of Chilean native wood species

We select the top 7 species from the remaining thirteen species represented in Figures 8, 9 and 10. Based on rankings of compressive parallel to grain stress, compressive perpendicular to grain stress and natural durability. The new ranking is then generated based on a physical attribute of native species that is its capacity to dry easily. The final selection criteria considers seven species. Information is compiled from the following references: [12] corresponding to B-113, [13] corresponding to B-144, [14] corresponding to B-145, and [15]corresponding to B-147.

In figure 11 is shown a ranking of the capacity of drying of Chilean native wood species.

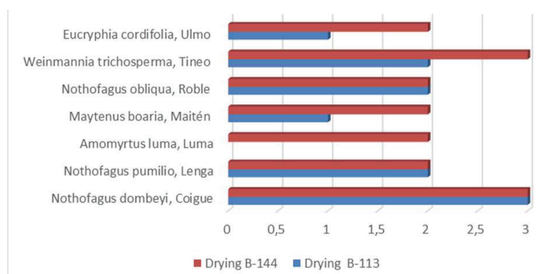

Figure 11 Ranking of the capacity of drying of Chilean native wood species.

The following four species with the best performance were chosen based on the final criterion C7.

Coigue (*Nothofagus dombeyi)*
Tineo (*Weinmannia trichosperma)*
Roble (*Nothofagus obliqua)*
Lenga (*Nothofagus pumilio)*

In table 1 is shown a comparison of Chilean native species filtered by price divided by cubic metre.

Table 1: Comparison of Chilean native species filtered by price divided by cubic metre ($/m3), own elaboration, according to [7].

Native species planed and nominal sizes	($/m^3)	Region
Coigue (*Nothofagus dombeyi)*	945	Malleco
Tineo (*Weinmannia trichosperma)*	561	Ranco
Roble (*Nothofagus obliqua)*	919	Llanquihue
Lenga (*Nothofagus pumilio)*	449	Ranco

3.2 GEOMETRY SELECTION RESULTS

Geometry studies were conducted to apply several structural systems to a particular geometry, as shown in the picture. The following literary works served as the foundation for the structure systems under study: reciprocal frame [16], "Armaduras de Lazo" as in [11], and as in Sebastiano Serlio's technique [17]. In Figure 12 is shown how a reciprocal frame based on a square with 2 jigs inscribed in a rectangle.

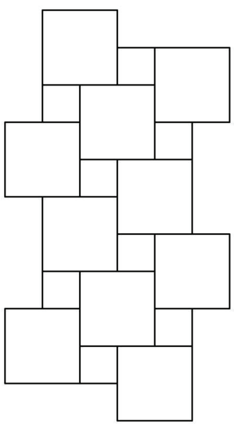

Figure 12 Reciprocal frame based on a square with 2 jigs.

The same wood section, a minimum number of jigs, and the simplest joints were the guiding principles for all geometrical analysis.

In Figure 13 is shown a plan of a standard panel prototype.

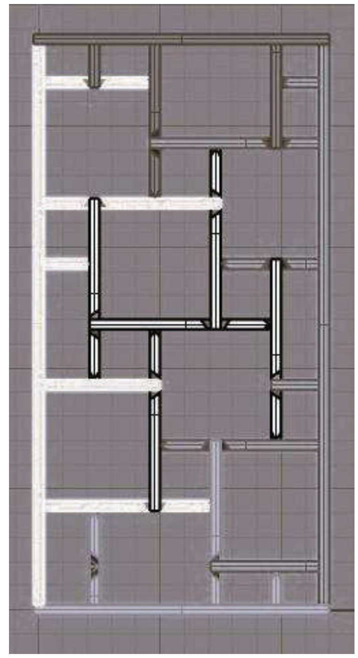

Figure 13 Plan of a panel prototype

When designing joints, we decided to optimise the production selecting 2 diagonal cuts instead of 2 verticals and 2 diagonals, as in Figure 14 and 15 respectively. Using this simplified type of batten fewer adjustments of the full-scale wood prototype are required.

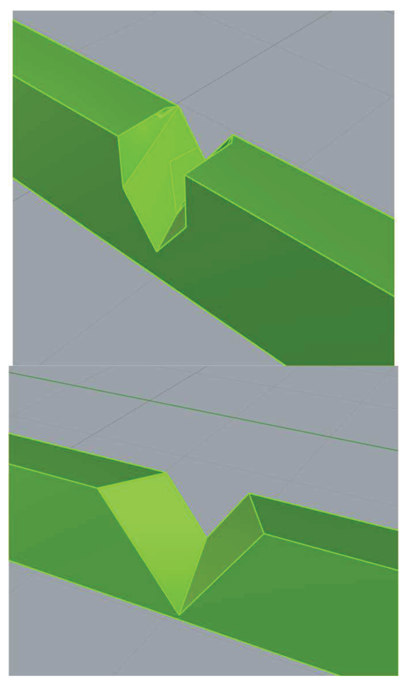

Figure 14 - 15 3D printed batten's prototype.

In Figure 16 is shown a 3D printed joint of two battens. In Figure 17 is shown a 3D printed portion of the prototype panel.

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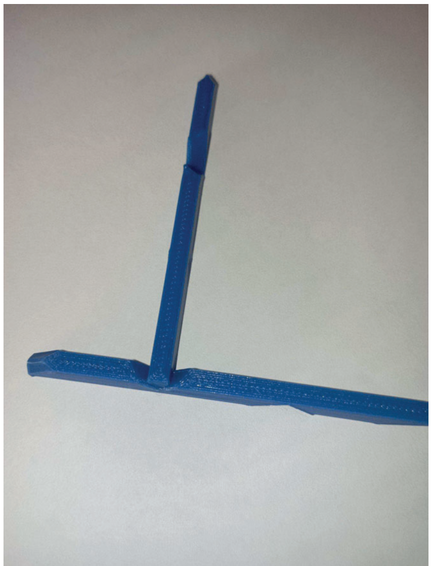

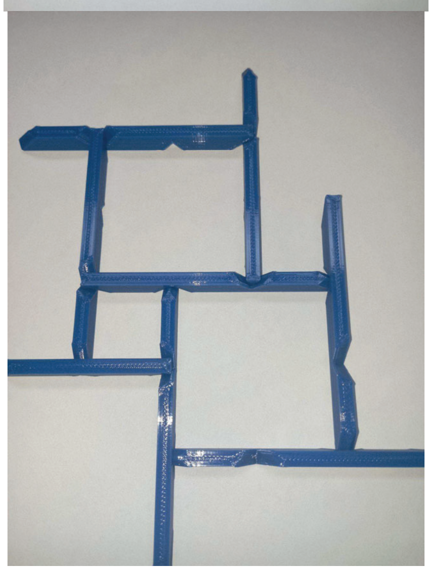

Figure 16 3D printed joint of two battens. **Figure 17** 3D printed portion of the prototype panel.

3.3 STRUCTURAL PRELIMINAR RESULTS

We calculated a traditional Radiata Pine (Pinus radiata) panel, and a Chilean native wood species based on a reciprocal frame geometry.

Seismic and wind loads were considered for the calculation of both panels. We considered a lateral load of 7 kN/m and a vertical load of 12,38 kN/m according to NCh 1537.

The results shown in the preliminary figures 18 and 19, demonstrate a smaller critical reaction in the first panel than in the second one, with 9,33 kN and 15,42 kN respectively. On the opposite, a smaller critical moment in the first panel than in the second one, with 2,03 kN/m and 0,32 kN/m respectively. Because critical reactions and critical moments are very close between both panels, we expect than the section required for the second panel is smaller because the mechanical properties of the Tineo (Weinmannia trichosperma) and the Roble (Nothofagus obliqua) are a lot better than the Radiata Pine (Pinus radiata) ones.

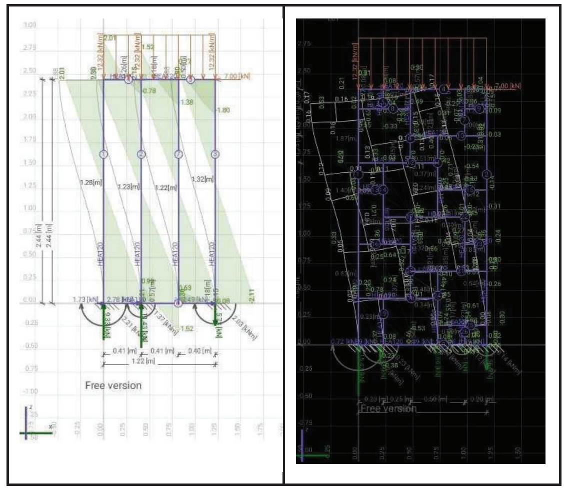

Figure 18-19 Preliminary traditional and reciprocal frame structural analysis

4. CONCLUSIONS

We conclude that it is conceivable to construct with small battens and large spans as a result of the study of geometry, notably the ancient structural principle known as reciprocal frames. Additionally, it is feasible to construct structural elements without using glue or any other chemical substances that have negative consequences for the environment. Radiata Pine (Pinus radiata) platform-frame systems used for walls or slabs can be swapped out for structural elements of a reciprocal frame.

Regarding the selection of native species, we decided to choose potential species that meet specific mechanical properties, a high natural durability, a high capacity to dry, and a low economic cost. We conclude that Tineo (*Weinmannia trichosperma*) is the species best suited for this purpose. His straight trunk can measure 40 m height and 2 m diameter. It would provide structural wood applications instead of current market use like finishes, veneer, or furniture. The second native species is Roble (*Nothofagus obliqua*). It was chosen to facilitate the prototype stage. Although this species has a less good drying capacity, it is easier to get due to its greater availability throughout Chile.

Regarding a geometric criterion, two sizes of square are the basis for the design of the chosen reciprocal frame. They are made from a single batten that is connected at two locations that are equally spaced from its edges. As a result, only two battens are needed, the bigger inner batten and the edge batten

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that often makes up a fraction of the batten, need to be built for each panel. The structural frame serves as the foundation for fitting the final panel. The prefabrication of the parts is optimised by this design, resulting in higher quality, more control, and reduced costs.

In terms of joint design, changes must be made to ensure that the shim and pressure prevent slippage and the transfer of mechanical stresses between battens by simplifying the junction with a diagonal cut on both sides. To assess whether additional design modifications or the use of reinforcing dowels are necessary, these alterations should be compared on a full-scale.

One of the research's current constraints is the flexibility provided by the 3D printed members. It only permits a limited fit between parts and requires adjustments in wood size prototypes in order to change the design parameters and enhance the prototype outcomes. The usage of the selected species for the creation of the scaled prototypes and ultimately the full-scale prototypes for testing and assessment will constitute the second stage of the research.

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